On Embedding Meta-ecosystems into a Socioecological Framework: A Reply to Renaud et al

Gounand, Isabelle ; Harvey, Eric ; Little, Chelsea J ; Altermatt, Florian

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On embedding meta-ecosystems into a socio-ecological framework

Authors: Isabelle Gounand[1,2,*], Eric Harvey[3], Chelsea J. Little[1,2] and Florian Altermatt[1,2]

*Corresponding author: Gounand, I. (isabelle.gounand@eawag.ch)

Addresses:

[1]Eawag, Department of Aquatic Ecology, Überlandstrasse 133, CH-8600 Dübendorf, Switzerland

[2]University of Zurich, Department of Evolutionary Biology and Environmental Studies, Winterthurerstr. 190, CH-8057 Zürich, Switzerland

[3]University of Toronto, Department of Ecology and Evolutionary Biology, 25 Wilcocks street M5S 3B2 Toronto, Ontario, Canada

E-mail addresses:

IG: isabelle.gounand@eawag.ch

EH: eric.harvey@utoronto.ca

CJL: chelseajean.little@eawag.ch

FA: florian.altermatt@eawag.ch

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Spatial flows of organisms and resources are increasingly recognized as key elements of ecosystem functioning [1,2]. In a previous article [3], we called for an update of the meta-ecosystem framework, a key conceptual and theoretical framework regarding spatial dynamics [4]. Specifically, we identified ways to better integrate different types of flows connecting ecosystems and their specific spatio-temporal scales in order to improve our understanding of ecosystem couplings. Building on this article, Roque et al. [5] wrote that, to be more predictive and operational, the meta-ecosystem framework should also explicitly include the socio-ecological mechanisms underlying the impacts of human societies on these flows. Their rationale is that socio-cultural mechanisms govern the way human society interacts with ecosystems and influence spatial flows connecting ecosystems. Roque et al. provide some case studies of such influence, for instance with the perception of ivory trade [6].

We see some potential value of such a socio-ecological perspective, for example to address specific questions about dynamical feedbacks between humans and the environment (e.g., on the environmental sustainability of human practices [7]). However, it is noteworthy that human-induced effects on meta-ecosystem dynamics are already integrated within the variation in spatial flow values considered in meta-ecosystem models (e.g., variance and mean quantity/quality of flows) [4]. Thus, studying the effects of processes acting at different scales on ecosystem functioning can already be achieved with the existing meta-ecosystem framework while avoiding additional layers of complexity, which might reduce interpretability and understanding.

As we illustrate with a strongly human-shaped landscape in our previous article [3], human activities influence the spatial flows linking ecosystems in various ways. This includes increasing some flows (e.g., leaching of agricultural fertilizers to aquatic systems), regulating the species

44 driving other spatial flows, or even modifying the landscape configuration itself. We here explain
45 one well-known example of the role of human activities in meta-ecosystems including all these
46 aspects (Fig. 1A): Geese populations in the southern United States massively increased following
47 agriculture intensification in the 1960's, because the geese shifted their diets from feeding in
48 wetlands to feeding on the augmented resources in agro-ecosystems [8]. This resource
49 augmentation was of course triggered by socio-economic changes in farming practices, and also
50 had effects on local meta-ecosystems (i.e., runoff into waterways). In the context of global meta-
51 ecosystems, the subsequent increase in flows of migratory birds dramatically affected arctic
52 tundra ecosystems [8], and this effect was partly modulated by hunting along the geese's
53 migratory routes, in itself a socio-cultural phenomenon.
54 Thus, along with Roque et al. [5] and others working on socio-ecological linkages [9,10], we
55 agree that culture and mental models are central to the people-nature relationship, and a crucial
56 link in the decision pathway leading to environmental regulation of anthropic impacts on nature
57 (e.g., land use management, hunting rules; see Fig. 1B, arrow 1). However, accounting for these
58 anthropic impacts can already be done by directly implementing the forcing derived from socio-
59 cultural processes on flows (e.g., in Fig. 1A adding fields and reducing migratory flow), without
60 explicitly modelling the socio-cultural processes in the meta-ecosystem framework.
61 Thus, when would the additional complexity brought by integrating mental models into the meta-
62 ecosystems framework be more useful than the pre-existing implicit consideration of human
63 influences in meta-ecosystems? We find that this may depend on the questions being addressed,
64 for example, when the focus is no longer on the meta-ecosystem dynamics themselves, but rather
65 on the long-term consequences of feedbacks between meta-ecosystem and socio-cultural

dynamics. This implies that the ecosystem services provided by meta-ecosystem dynamics ([11], arrow 2 in Fig. 1B) strongly feed back on mental models (arrow 3); in the geese example, this would happen if tundra loss is sufficiently important for public opinion to change agricultural or hunting practices towards "tundra-sustainable" ones. To analyse such scenarios, the meta-ecosystem framework could be embedded into a socio-ecological perspective in stylized models explicitly focusing on these feedback links (bold arrows in Fig.1B), similarly to approaches proposed in the study of biodiversity – human society interactions [7]. In such models, however, explicit consideration of meta-ecosystem dynamics is not needed, merely the effects that these meta-ecosystem dynamics produce on ecosystem properties of values for humans.

In conclusion, to our opinion, zooming in the meta-ecosystem box (Fig. 1B), or zooming out on the socio-ecological feedback loop, relates to different questions, which might be better addressed with different modelling frameworks (meta-ecosystem *versus* socio-ecological). In that context, we suggest that the interactions between socio-cultural processes and meta-ecosystem dynamics should be addressed in an iterative scientific process through planned collaborations, as has been proposed for coordinating exchanges between theory and empirical work [12]. Thus, the results of one perspective can inform the other, better hypotheses can be tested, and our understanding can be bolstered by strong inference, without all processes necessarily being integrated into one framework.

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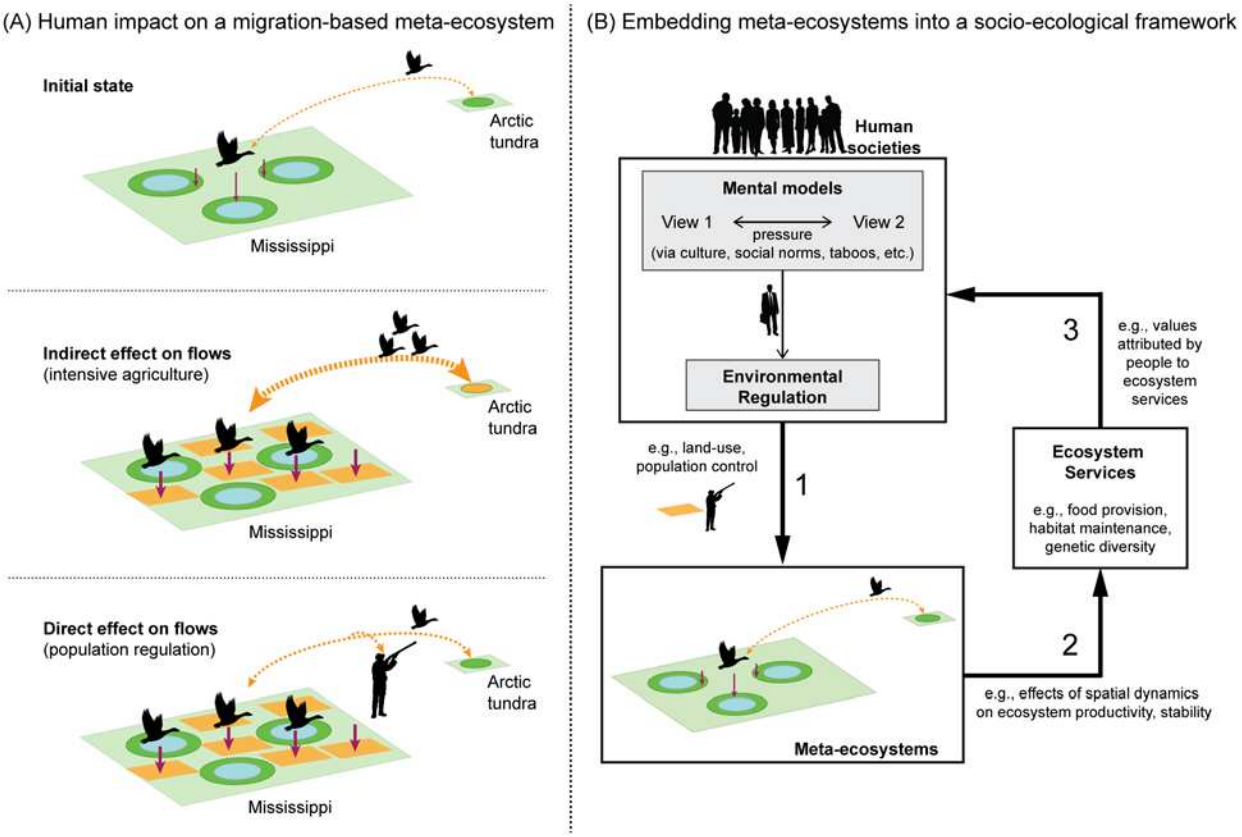

Figure 1. Meta-ecosystems in the Anthropocene. (A) The left panels show an example of human impacts on meta-ecosystem dynamics with the emblematic case-study on migratory geese linking resource flows between the Mississippi basin with the arctic tundra (top panel): agriculture intensification in the Mississippi in the 1960's (fields in yellow) increased geese food supply (foraging arrows in magenta), which resulted in higher abundance of migratory geese and associated nutrient flow to the tundra (dotted yellow arrow), triggering catastrophic shifts of arctic communities ([8]; middle panel); hunting on the migratory road illustrates a direct human impact on spatial flow (flow reduction; bottom panel). (B) Meta-ecosystems can be embedded in a socio-ecological framework. Within human societies, culture and social norms drive the dominance of some views in the public opinion regarding the interaction between humans and

126 nature (e.g., profit versus non-profit views on ivory trade [6]). These mental models influence
127 environmental regulation, which modulates the impact of human activities on spatial flows and
128 meta-ecosystem dynamics (e.g., through rules on land-use or hunting; arrow 1). Meta-ecosystem
129 dynamics affect ecosystem properties, such as productivity, or biodiversity, which provide
130 services to people (arrow 2). Depending on the value that people attribute to these ecosystem
131 services, change in meta-ecosystem dynamics might feedback on mental models (arrow 3), for
132 instance (example panel A) the public opinion might shape hunting practices and regulations.